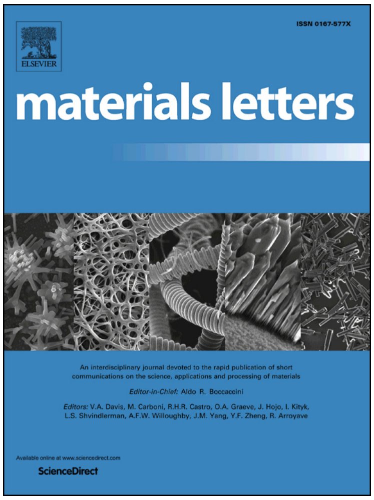

Determination of retained austenite using CCE model accounting for isothermal transformation in a low density quenched and partitioned steel

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Determination of retained austenite using CCE model accounting for isothermal transformation in a low density quenched and partitioned steel

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Abstract:

This work aims at broadening water quenching window for production of hot rolled quenched and partitioned (Q&P) steels. Comparing with conventional researches, a low density steel 0.25C-3Mn-2Al (wt.%) was designed to increase the amount of retained austenite (RA) through quenching and non-isothermal partitioning processes. The results indicated that stable amount of RA greater than 19.3% was obtained in the quenching temperature range of ~ 280-360 ℃, resulting in excellent plasticity ~ 19.2-20.5% in combination with high tensile strength of ~ 1091-1196 MPa. The isothermal transformation was responsible for the stable amount of RA and the CCE model combining with isothermal transformation was used to quantitatively calculate RA.

Key words: Quenching and non-isothermal partitioning; Microstructure; Retained austenite; Phase transformation.

1. Introduction

Quenched and partitioned (Q&P) steels [1] are promising advanced high strength steels because of high strength-high ductility combination. Retained austenite (RA) contributed largely to plasticity and was main focus~~ to control~~. Conventional studies indicated drastic changes in amount of RA at different quenching temperatures (QT), generally leading to sacrifice of elongation at high strength. ~~L. ~~Liu *et al.* [2] reported that RA decreased to 9% from 18% as QT decreased to 150 °C from 240 °C and Seo *et al.* [3] indicated that the fluctuation of plasticity was related to the amount of RA. Therefore, control of ~~quenching temperature (QT)~~QT was significantly important. For prediction of RA, CCE model [1] was proposed and ~~it ~~gave the optimal QT. However, excellent performance could be only obtained at optimal~~a fixed~~ QT, leading to a narrow processing window~~ for Q&P treatment~~. Given that QT was complicated to control in large-scale sheet, especially during water quenching in hot production line, it was necessary to ensure sufficient RA and excellent mechanical properties at a wide range of QT.

This study worked for broadening water quenching window ~~during hot rolling-direct quenching and non-isothermal partitioning processes (DQ&P)~~in hot rolled Q&P steels [4]. Microstructures were designed containing sufficient RA with low correlation with QT, thereby solving the problem of plasticity fluctuation.

2. Material and methods

A low density steel ~ 0.25C-3Mn-2Al (wt%) was designed to satisfy basic constraints for Q&P treatment and kinetics criteria of non-isothermal carbon partitioning. More C and Mn were added to increase amount of RA, and 2% Al was added to increase M_s. The M_s was measured to be 370 °C using DIL 805 dilatometer. The billets with thickness of 40 mm were heated to 1200 °C and held for 2h followed by two stages of rolling procedures with finish rolling temperature of ~ 880-900 °C and thickness of 4 mm. In order to control QT precisely, water quenching was replaced by air cooling, because of excellent hardenability of the steel. Five plates were air cooled to 360, 340, 320, 300 and 280 °C, respectively, followed by cooling in furnace. For convenience, they are referred as A360, A340, A320, A300 and A280, respectively.

3. Results

Five samples contained multi-phases ~~microstructures~~ of ferrite, martensite, bainite and retained austenite. Fig.1a shows the microstructure~~s~~ of A280. The distribution of microstructure was closely related to grain boundary wetting and some study indicated that phase transformation was a surface wetting process from incomplete to complete depending on grain boundary (GB) energy [5, 6]. As can be seen from Fig. 1a, majority of ferrite grain boundaries (GBs) was completely wetted by γ-Fe layers and the transformed austenite. Thus, the ferrite grains were separated from each other. The phase fraction was quantitatively counted in Fig. 1b and RA was not counted individually, because it was embedded in bainite and martensite. It was interesting that A360 contained the highest amount of bainite ~ 36%, whereas ~ 25-30% bainite was obtained in samples air cooled to ~ 280-340 ℃. The bainite was formed during air cooling and furnace cooling processes. In addition, A280 was further characterized by TEM. As shown in Fig. 1c and d, ~~the~~ martensite lath was ~~about~~ ~ 95 nm and ~~the~~ RA exhibited two types of morphologies. The average width of lath RA between martensite was ~~about~~ ~ 45 nm, while the blocky RA at ferrite interfaces attained submicron level. By contrast, the lath RA embedded in bainite approached ~ 320 nm (Fig. 1e), which implied that bainite could promote formation of RA.

The RA was quantitatively calculated using CCE model. The carbon concentration with equal activity in α and γ during ~280-360 ℃ was plotted in Fig. 2a and it revealed significant difference of carbon in ferrite and austenite. Therefore, an assumption of ~~full~~ complete carbon partitioning was reasonable ~~to calculate CCE model~~. Finally, the amount of RA$_{CCE}$ was calculated in Fig. 2c. It indicated a ~~shape of~~ peak and the maximum ~24.1% was attained at 240 ℃. However, when QT was above 300 ℃, the RA$_{CCE}$ decreased sharply, which was attributed to an excess of initial austenite fraction and limit of carbon ~~for stabilizing austenite~~. High QT was necessary for adequate carbon diffusion during slow cooling in furnace.

That is, the CCE model seemed to deny DQ&P process. However, remarkable austenite peaks were observed at ~ 280-360 ℃ (Fig. 2b) and the measured RA was plotted in Fig. 2c. Comparing with CCE model, the measured RA was ~ 19.3-22.7% during QT of ~280-360 ℃, indicating a small difference less than 3.4%. The large fraction and stable amount of RA are conducive to excellent plasticity during a wide QT range.

Fig. 3 shows tensile curves and mechanical properties. The ultimate tensile strength (UTS) was increased to 1196 MPa from 1091 MPa ~~when the~~with decreased QT ~~was decreased~~ to 280 ℃ from 360 ℃. It was, however, interesting that ~~the~~ total elongation (TE) exhibited no sacrifice with increased strength and was always between 19-21 %, resulting in high PSEs greater than 21 GPa.%. In addition, the uniform elongation (UE) was greater than 13%, which also exhibited low correlation with QT.

4. Discussion

In this study, it revealed a phenomenon against strength-plasticity trade-off ~~at different quenching temperatures~~. The stable plasticity ~19.2-20.5% was obtained at a wide QT window (Fig. 3b). This abnormal plasticity was attributed to ~~design of microstructures~~microstructural design. First, ~~the~~ multi phases of ferrite, martensite/bainite and RA possessed outstanding deformation ~~capacity~~ability. Additionally, ~~the~~ large amount of RA ~ 19.3-22.7% not only could accommodate large strain, but also continually experienced TRIP effect. Consequently, the large fraction of RA could make up the disadvantage in conventional researches, where the small difference in amount of RA caused by QT generated big fluctuation of plasticity. In addition, the high strength greater than 1091 MPa ~~could be achieved, which~~ was attributed to the ultra-fine martensitic laths (about 100 nm). ~~It should be pointed out that~~The RA played a key role in determining the mechanical properties. Two types of RA (Fig. 1) with different stabilities were reported to provide continuous TRIP effect during tensile deformation [4]. In addition, the stable amount of RA was another essential factor for impressive performance and needed further discussion.

CCE model assumed that the as-quenched austenite $f_{\gamma-KM}$ based on K-M equation fully participated in carbon partitioning. Thus, when the QT was above optimal value, the carbon was insufficient to stabilize austenite, finally remaining little $\mathrm{RA}_{\mathrm{CCE}}$ (Table 1). In order to clarify the mechanism of non-isothermal partitioning, the phase transition of A280, A320 and A360 was observed. Fig. 4a shows the dilatation curve of A320 and it indicated obvious isothermal expansion ~~during tens of seconds~~ after quenching. In fact, the isothermal transformation below M_s has been reported~~ by some studies~~ [7]. Here, the isothermal transformation decided ~~the~~ final ~~proportion of~~ austenite that participated in carbon partitioning and should be used to correct CCE model. The proportion of isothermal transformation $f_{\alpha-ISO}$ was calculated using ratio of dilatation. Finally, the actual proportion of austenite that participated in carbon partitioning was calculated as $f_{\gamma-ISO}$. It can be seen from Table 1 that the $f_{\gamma-KM}$ before isothermal transformation had a large proportion and indicated huge difference, resulting in little $\mathrm{RA}_{\mathrm{CCE}}$ less than 6.5%. After considering isothermal transformation, the austenite fraction $f_{\gamma-ISO}$ was very close and the retained austenite after full carbon partitioning was calculated as $\mathrm{RA}_{\mathrm{ISO}}$. The total $\mathrm{RA}_{\mathrm{CCE}}$ and total $\mathrm{RA}_{\mathrm{ISO}}$ accounting for ferrite fractions were calculated in Table 1. The total $\mathrm{RA}_{\mathrm{ISO}}$ consequently gave wonderful fit~~ting~~ with measured RA in Fig. 4b. In summary, stable amount of RA could be promoted by isothermal transformation and a wide water quenching window could be obtained during hot rolled Q&P production.

5. Conclusion

The stable amount of RA ~ 19.3-22.7% can be obtained during QT range of ~280-360 °C through alloy design, which ensured excellent plasticity ~ 19.2-20.5%. The ultra-fine martensite lath ~~about~~ ~ 100 nm made the tensile strength greater than 1091 MPa. The CCE model accounting for isothermal transformation during slow cooling process could be used to quantitatively calculate RA.

6. Acknowledgements

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7. Declarations of interest

None

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Table and Figures

Table 1. Calculation of retained austenite accounting for isothermal transformation.

QT (°C)	$f_{\alpha-KM}$	$f_{\gamma-KM}$	RA_{CCE}	$f_{\alpha-ISO}$	$f_{\gamma-ISO}$	RA_{ISO}	Total RA_{CCE}	Total RA_{ISO}
360	0.104	0.896	0.025	0.677	0.219	0.219	0.053	0.220

320	0.423	0.577	0.033	0.342	0.235	0.235	0.060	0.234
280	0.628	0.372	0.065	0.169	0.203	0.203	0.086	0.207

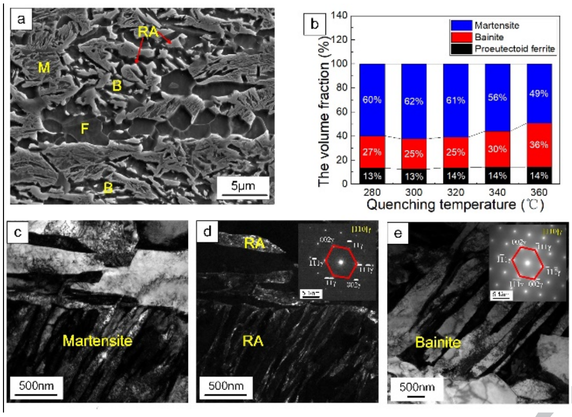

Fig. 1. The SEM micrograph of A280 in (a), phase fractions of five samples in (b) and TEM micrographs of A280 in (c)-(e).

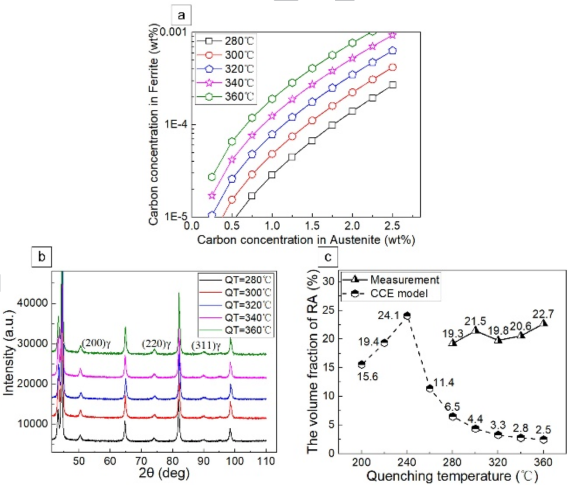

Fig. 2. Calculated locus of ferrite and austenite compositions having equal carbon activities at ~ 280-360 ℃ in (a), XRD patterns of (b) and comparison of the amount of RA based measurement and CCE model calculation in (c).

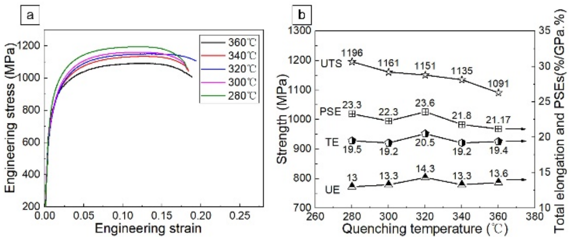

Fig. 3. Tensile curves in (a) and mechanical properties as a function of quenching temperature in (b).

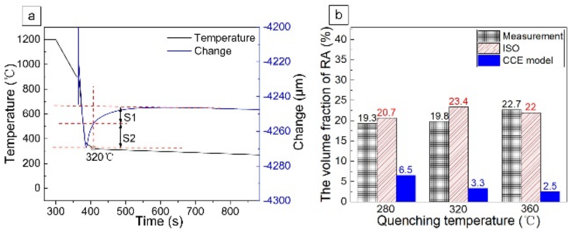

Fig. 4. Isothermal transformation during non-isothermal partitioning at cooling rate of 0.1℃/s in (a) and comparison of retained austenite in (b). S1 and S2 represent the dilatation of quenching and isothermal transformation, respectively.

- A low density alloy was designed to increase the amount of retained austenite.
- 19.3-22.7% RA can be obtained at quenching temperature (QT) of ~280-360 ℃.
- Excellent plasticity ~ 19.2-20.5% can be obtained at a wide QT window.
- Ultra-fine martensite lath makes tensile strength greater than 1091 MPa.
- The isothermal transformation promotes stable amount of RA.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of interests

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☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: